

# Single-mode, All-Solid-State Nd:YAG Laser Pumped UV Converter

Narasimha S. Prasad<sup>1</sup>, Darrell J. Armstrong<sup>2</sup>, William C. Edwards<sup>1</sup>, Upendra N. Singh<sup>1</sup>

<sup>1</sup>NASA Langley Research Center, 5 N. Dryden St., MS 468, Hampton, VA 23681, USA,  
narasimha.s.prasad@nasa.gov

<sup>2</sup>Sandia National Laboratories, Dept. 1128, Albuquerque, NM 87185-1423, USA

## ABSTRACT

In this paper, the status of a high-energy, all solid-state Nd:YAG laser pumped nonlinear optics based UV converter development is discussed. The high-energy UV transmitter technology is being developed for ozone sensing applications from space based platforms using differential lidar technique. The goal is to generate greater than 200 mJ/pulse with 10-50 Hz PRF at wavelengths of 308 nm and 320 nm. A diode-pumped, all-solid-state and single longitudinal mode Nd:YAG laser designed to provide conductively cooled operation at 1064 nm has been built and tested. Currently, this pump laser provides an output pulse energy of >1 J/pulse at 50 Hz PRF and a pulsewidth of 22 ns with an electrical-to-optical system efficiency of greater than 7% and a  $M^2$  value of <2. The single frequency UV converter arrangement basically consists of an IR Optical Parametric Oscillator (OPO) and a Sum Frequency Generator (SFG) setups that are pumped by 532 nm wavelength obtained via Second Harmonic Generation (SHG). In this paper, the operation of an inter cavity SFG with CW laser seeding scheme generating 320 nm wavelength is presented. Efforts are underway to improve conversion efficiency of this mJ class UV converter by modifying the spatial beam profile of the pump laser.

## 1. INTRODUCTION

NASA is actively engaged in the development of space-based active remote sensing missions using lidar techniques. To develop reliable and robust laser based lidar systems, NASA began the Laser Risk Reduction Program (LRRP) in 2002 [1]. Jointly run by Langley Research center and Goddard Space Flight Center, the LRRP is designed to advance laser performances as well as to mitigate associated risks in critical components such as pump diodes for remote sensing applications from space based platforms. The technical objective of LRRP is to develop high-energy, solid-state, conductively cooled and single longitudinal mode 1 micron and 2 micron lasers and appropriate wavelength conversion technologies suitable for four lidar techniques namely altimetry, Doppler, Differential Absorption Lidar (DIAL), and basic backscatter signal strength profiling. These four techniques would enable six priority earth science measurements of surface and ice mapping, horizontal vector wind profiling, river

currents monitoring, carbon dioxide (CO<sub>2</sub>) profiling, ozone (O<sub>3</sub>) profiling, and aerosols/clouds monitoring. The overall goal of LRRP is to advance laser technologies to the point that science mission proposals could be confident of acceptable risk upon selection.

For ozone profiling, efficient 1-micron to UV wavelength conversion technology to generate tunable, pulsed UV wavelengths of 308 nm and 320 nm is being pursued. Accordingly, the diode-pumped Nd:YAG laser has been developed to pump a nonlinear optics based UV converter arrangement to generate 320 nm and 308 nm wavelengths. The scheme is to pump the nonlinear optics arrangement by 532 nm wavelength that is obtained from the 1064 nm wavelength via second harmonic generation (SHG) process using a KTP crystal. The nonlinear optics arrangement basically consists of a novel optical parametric oscillator (OPO), known as Rotated Image Singly Resonant Twisted Rectangle (RISTRA) module and a sum frequency generation (SFG) crystal coupled to a CW tunable diode laser based seeding setup. To obtain 320 nm, the RISTRA OPO is configured to generate 803 nm that is subsequently mixed with 532 nm using a SFG crystal. In the second case, the RISTRA OPO generates 731.5 nm which when mixed with 532 nm generates 308 nm. Round and flat top pump beam profile is preferred for optimal RISTRA OPO operation to achieve optimal UV conversion efficiency. Several seeding schemes including pulse idler seeding have been successfully demonstrated. Modeling and simulation studies have indicated the requirement of high pulse energy of >200 mJ with low pulse repetition rates at UV wavelengths to achieve enhanced performance during strong daylight conditions. This high energy low repetition rate UV transmitter scheme with space qualified packaging is anticipated to provide sensitive measurements for atmospheric ozone profiling using differential absorption lidar (DIAL) technique from space-based platforms.

The viability of the above nonlinear optics based arrangement comprising of an optical parametric oscillator (OPO) and a sum frequency generator (SFG) to obtain >200 mJ/pulse at UV wavelengths has been established under laboratory conditions. The RISTRA configuration has demonstrated to provide enhanced output beam quality. So far, the RISTRA OPO has

demonstrated greater than 90 % pump depletion and greater than 24% IR-UV optical conversion efficiencies with stable mode quality [2-4]. For our initial experiments, a flash lamp pumped Nd:YAG laser was used. However, our goal is to pump the UV converter arrangement with an all solid-state pump laser. Hence, the diode pumped Nd:YAG laser development was pursued in parallel to the development of UV converter technology [5].

## 2. THE DIODE-PUMPED ND:YAG LASER

For flight worthy and space-qualifiable systems, compact, conductively cooled, and solid-state design configuration is vital [6,7]. A single frequency pump source to generate UV wavelengths is required for efficient differential absorption lidar (DIAL) measurement of ozone. The high energy pump laser was achieved by upgrading a 300 mJ/pulse Nd:YAG laser that was developed under NASA's Advanced Technology Initiative Program (ATIP). This ATIP laser consisted of a ring oscillator and dual amplifiers, Amplifier 1 and Amplifier 2 [8,9] and operated at 50 Hz. Amplifiers 3 and 4 have been added to obtain output energy greater than 1.0 J/pulse. The diode pumping increases efficiency and reduces size and weight. Conduction cooling eliminates circulating liquids and increases MTBF values. The goal is to obtain high beam quality, that facilitates a reduction in the size of the transmit optics, and to enhance the nonlinear conversion processes used to produce the desired UV wavelengths.

The technical approach for the development of a reliable, robust and efficient diode-pumped Nd:YAG pump laser is based on an oscillator/amplifier design configuration [10]. The important features of the all solid-state pump laser are as follows: (a) injection seeded ring laser that improves emission brightness ( $M^2$ ), (b) diode-pumped zigzag slab amplifiers that allow robust and efficient design for use in space environment, (c) advanced electro-optic phase modulator material that allows high frequency cavity modulation for improved stability injection seeding, (d) alignment insensitive/boresight stable 1.0 mm cavity and optical bench for achieving stable and reliable operation, (e) conduction cooled operation that eliminates circulating liquids within cavity, and (e) space-qualifiable component designs that establishes a path to a space-based mission. The optical layout of the Nd:YAG pump laser is illustrated in Figure 1. The ATIP laser consists of an oscillator head, amplifier 1, amplifier 2, amplifier 3, and amplifier 4. To control output energy, each amplifier can be operated individually or in combination. Considerable progress has been made in the design, fabrication and testing of this diode pumped Nd:YAG pump laser.



Figure 1. The diode-pumped Nd:YAG laser unit.

## 3. THE UV CONVERTER

For technology demonstration, initial experiments to generate 320 nm were carried out using a flash lamp pumped modified Continuum Powerlite 9010 Nd:YAG laser operating at 10 Hz PRF. Flat top spatial profiles for the pump beam was utilized to achieve maximum conversion during nonlinear optical processes. Accordingly, a refractive beam shaper and vacuum imaging-telescope with 3 mm diameter scraper were used to achieve flat-top profiles [5]. The 1064 nm beam was converted to 532 nm beam using a xy-cut KTP  $2\omega$  (SHG) crystal. Using maximum pulse energy at 1064 nm of  $\sim 900$  mJ, the  $2\omega$  efficiency achieved was  $\sim 70\%$ . Several techniques for increasing the conversion efficiency of OPO and SFG interaction process were incorporated. The image-rotating non-planar-ring OPO cavity known as RISTRA geometry was used to enhance the OPO conversion efficiency. RISTRA is an acronym for Rotated-Image Singly-resonant Twisted RectAngle. It provides excellent output beam quality with high Fresnel numbers that is essential for achieving higher SFG conversion efficiencies. Invented at Sandia National Labs, the RISTRA configuration has shown to provide high pump depletion and high output beam quality. The RISTRA OPO configuration conveniently allowed larger pump beam diameters and hence, high energy and low fluence than those possible in conventional OPO setups.

In the case of a flash lamp based UV converter experiments, idler pulse seeding technique was employed with extra cavity SFG arrangement to generate  $> 200$  mJ/pulse. The pump depletion greater than 90 % has been demonstrated. The IR-to-UV efficiency of  $> 21\%$  with 500 microjoule of seed energy has been achieved. Greater than 27% conversion efficiency has been achieved for 1 mJ of seed energy. Smooth, round, and flat-top pump beams were utilized to obtain high efficiency for OPO and SFG interactions. The fluence was  $\leq 1$  J/cm<sup>2</sup> for most beams. Pump depletion was found to be greatest for flat-top pump

and seed beams. The technical approach is similar for generating 308 nm except that the IR OPO will generate 731.5 nm for mixing with 532 nm. Pulsed injection seeding known as “self seeding” allowed build-up time to be  $\approx 0$  for identical signal and pump temporal profiles and that optimized beam quality for subsequent SFG process. However, the overall scheme was relatively complex.

To simplify overall configuration, CW laser seeding coupled to an inter cavity SFG is also being currently investigated. Figure 2 illustrates the experimental setup. The CW seed laser operating at 803 nm from New Focus was used as the seed source. The RISTRA OPO configuration along with the compact mechanical mount is shown in Figure 3.

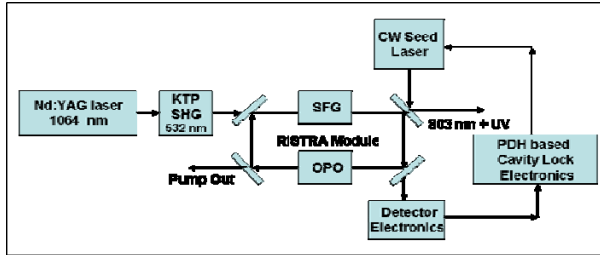


Figure 2. The CW laser seeded inter cavity SFG based UV converter scheme.

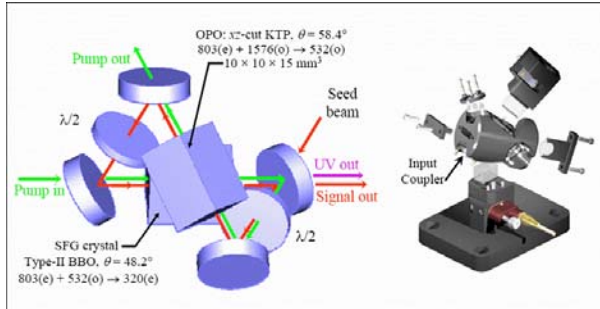


Figure 3. The RISTRA OPO configuration and the opto-mechanical module.

For our experiments, the RISTRA OPO utilized a xz-cut KTP with  $\theta = 58.4^\circ$ ,  $532(o) \rightarrow$ , where  $803(e) + 1576(o)$  and the SFG utilized a Type-II BBO crystal with  $\theta = 48.2^\circ$ ,  $803(e) + 532(o) \rightarrow 320(e)$  where  $\theta$  is the phase matching angle, o as the ordinary beam and e is the extraordinary beam. Using a custom designed Pound-Drever-Hall scheme, the seed laser was locked to the OPO cavity. The OPO and the SFG crystal phasematching angles were individually optimized using the joy stick connected to the picometer control hardware. When the phase mismatch was nearly zero, one could see the periodic increases in the signal energy as the laser sweeps through the cavity resonance.

#### 4. RESULTS AND DISCUSSION

The UV converter was effectively coupled to the diode pumped Nd:YAG laser and was made operational. The RISTRA module consisting of the OPO and SFG crystals is shown in Figure 4. Typical depleted pump, OPO signal and UV signal characteristics are shown in Figure 5.

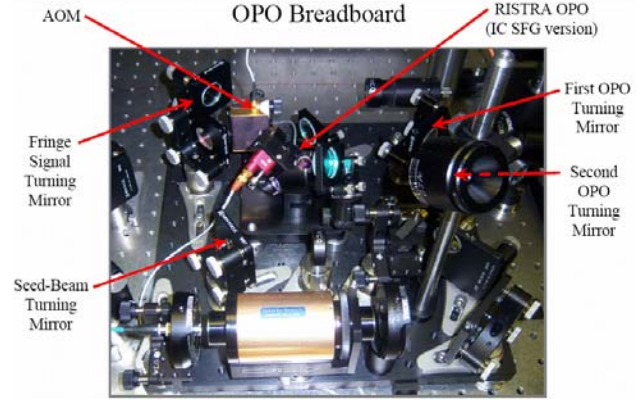


Figure 4. The RISTRA OPO setup with inter cavity SFG crystal.

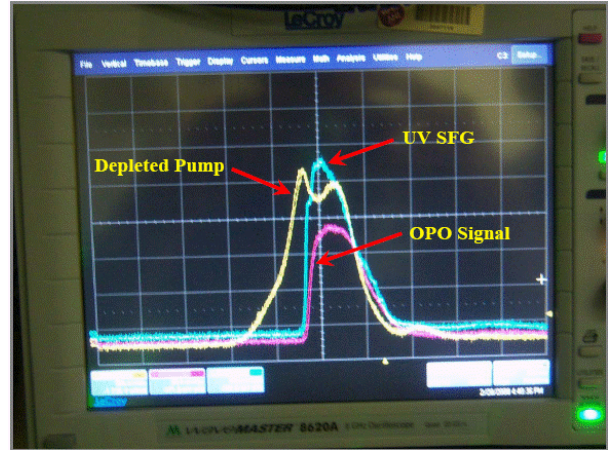


Figure 5. The temporal characteristics of depleted pump at 1064 nm, the OPO signal at 803 nm and UV signal at 320 nm.

At present, the output UV energy at 320 nm is estimated to be few mJ. This is due to the nature of output beam profile of the Nd:YAG laser beam that is mismatched to the RISTRA OPO cavity. The near-field beam profile characterization of the Nd:YAG pump laser showed that it was close to Gaussian profile. However, the beam profile that was incident on the KTP crystal for generating 532 nm was astigmatic with structures. Since the RISTRA OPO cavity with image rotation feature requires round profiles for optimal nonlinear interaction, the current astigmatic pump beam severely reduced the overlap. As a result, the maximal pump depletion due to OPO interaction was not

achieved. So far, the estimated pump pulse energy used is only about 200 mJ. Accordingly, efforts are underway to improve the beam profile of the Nd:YAG laser pump beam to enhance IR-UV conversion efficiency.

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